Renewable and Sustainable Energy Reviews 16 (2012) 5529–5534

Contents lists available at SciVerse ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

A simplified method for estimating direct normal solar irradiation from global horizontal irradiation useful for CPV applications

P.J. Pérez-Higueras, P. Rodrigo*, E.F. Fernández, F. Almonacid, L. Hontoria

Electronic Engineering and Automatic Department—Jaén University, Las Lagunillas Campus, A3 building, 23071 Jaén, Spain

ARTICLE INFO

Article history:
Received 11 November 2011
Received in revised form
22 May 2012
Accepted 26 May 2012
Available online 9 August 2012

Keywords:
Concentrator photovoltaics
Direct normal irradiation
Solar radiation model

ABSTRACT

The design and analysis of CPV systems require knowledge of direct normal solar irradiation but ground-based measurements of these data are only available for very few locations. Nowadays, meteorological databases that estimate direct normal irradiation from satellite images and other data sources are used. However, values provided by the different existing databases show large dispersion due to different estimation methods, input data and base years. In this paper, a simplified method for calculating direct normal irradiation is presented. It has been obtained from previous models proposed by several authors. One of its advantages is that it only requires latitude and global horizontal irradiation as input data. As global irradiation is easy to find or measure, the procedure becomes a useful tool in renewable energy applications. The accuracy of this method is similar to that of the existing databases and it is able to easily generate a mass of direct normal irradiation data for different areas worldwide.

Contents

1. Introduction

Photovoltaic devices are at a mature technological stage with a long and wide field experience, but if this energy source wants to compete against other renewable energy sources or even to get into the traditional energy generation system, further scientific progress in the behavior of these kinds of systems is necessary. Concentrator Photovoltaic (CPV) technology can have a main role in this challenge, as it has proved, in recent published research, to have the potential to achieve high levels of energy conversion performance [1].

CPV is based on the use of optical devices that increase the light received on the solar cell surface. The concentration mechanism is achieved by lenses or mirrors that either refract or reflect the incoming light from the sun on top of the cell receiver surface. Depending on the concentration process, as well as on the concentration area, there is a wide range of optical device configurations that can be used in the implementation of a CPV module [2].

The use of concentrators implies that CPV systems only work with the Direct Normal Irradiance (DNI). So it is necessary to know DNI data in order to estimate the energy that will be produced by the system, perform economic analysis, supervise plant operation, etc. However, DNI ground-based measurements

Abbreviations: CPV, concentrator photovoltaic; DNI, direct normal irradiance or irradiation; TMY, typical meteorological year; HC, HelioClim; HCPV, high concentration photovoltaic

* Corresponding author. Tel.: +34953212924; fax: +34953211967.
E-mail addresses: pjperez@ujaen.es (P.J. Pérez-Higueras), prodrigo@ujaen.es (P. Rodrigo), fenandez@ujaen.es (E.F. Fernández), facruz@ujaen.es (F. Almonacid), hontoria@ujaen.es (L. Hontoria).

1364-0321/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.rser.2012.05.041

Nomenclature

B_0	solar constant (W/m^2)
δ_{dn}	solar declination of the day in the middle of each month (radians)
d_n	day number of the year (dimensionless)
$\varepsilon_{o\ dm}$	eccentricity correction factor of the earth's orbit of the day in the middle of each month (dimensionless)
$G_{G\ hm}(0)$	monthly average hourly global irradiance on a horizontal surface (W/m^2)
$G_{B\ hm}(0)$	monthly average hourly direct irradiance on a horizontal surface (W/m^2)
$G_{D\ hm}(0)$	monthly average hourly diffuse irradiance on a horizontal surface (W/m^2)
$G_{B\ hm}(S)$	monthly average hourly direct normal irradiance (W/m^2)
$H_{G\ dm}(0)$	monthly average daily global irradiation on a horizontal surface (Wh/m^2)
$H_{BO\ dm}(0)$	monthly average daily extraterrestrial irradiation on a horizontal surface (Wh/m^2)
$H_{B\ dm}(0)$	monthly average daily direct irradiation on a horizontal surface (Wh/m^2)
$H_{D\ dm}(0)$	monthly average daily diffuse irradiation on a horizontal surface (Wh/m^2)
$H_{B\ dm}(S)$	monthly average daily direct normal irradiation (Wh/m^2)
$H_{B\ a}(S)$	annual direct normal irradiation (Wh/m^2)
K_{Tm}	clearness index (dimensionless)
K_{Dm}	diffuse fraction of global radiation (dimensionless)
φ	latitude (°)
ω	solar hour angle (radians)
$\omega_{s\ dm}$	Sunrise hour angle of the day in the middle of each month (radians)

are expensive and rarely available due to the cost and sophistication of measurement devices and data processing requirements. There is a particular lack of data in the Sunbelt countries, which are more favorable for the use of CPV.

This lack of DNI data contrasts with the availability of global horizontal irradiation data, which are easy to find or measure. So it seems to be interesting to have a procedure that obtains DNI from global irradiation.

We can find in the literature several models for calculating DNI from different parameters [4–8]. These models are accurate but some of them are complex and difficult to apply, especially because they require input data that is not easy to obtain, for instance measurements taken from satellite images. In this paper, a simplified method obtained from previous models is presented. Its aim is not to improve the existing models, but to easily provide DNI only by using latitude and global horizontal irradiation as input data. The accuracy of the method seems to be acceptable for its use in CPV applications.

2. DNI data sources

Preferably, Typical Meteorological Year (TMY) data should be used for the analysis and design of CPV systems. These datasets are based on measurements taken from ground meteorological stations for ten years [3]. However, due to equipment costs, such measurements are scarce and TMY datasets are available for only a very few locations. An alternative solution to this problem is the use of a model that derives DNI from satellite data. In recent years, several methods for estimating direct normal irradiance and irradiation from satellite data have been proposed [4–8]. Nevertheless, the use of these procedures is often difficult as is obtaining the satellite data. Thus, spatial databases that directly provide DNI are usually utilized.

There are a number of spatial databases that provide DNI values for different places and time intervals (Meteonorm [9], NASA-SSE [10], PVGIS [11], PVSAT [12], Satel-Light [13], SoDa [14], SOLEMI [15], etc.). These databases use different kinds of input data (satellite data, ground-based measurements) and different procedures in order to estimate DNI values. They are a very useful tool for the design and evaluation of CPV systems. However, some databases show weaknesses: there is a lack of continuity in the data because the information comes from a limited number of ground stations and there are no hourly DNI data, except for a very few sites. Although the main problem is uncertainty because DNI values provided by the different databases show large dispersion. The result is a fragmentation of services, each having its own mechanism of access and all giving different outputs due to different methods, input data and base years.

In order to analyze this uncertainty, a comparison between measured DNI values taken from ground meteorological stations located at three Spanish places (Madrid, 40.417N –3.700W; Murcia, 37.983N 1.130W and Jaén, 37.766N–3.790W) and DNI values provided by three databases (SoDa, NASA-SSE and PVGIS) for these three locations has been made.

DNI measurements for Madrid have been carried out by the Solar Energy Institute (Instituto de Energía Solar, IES) in 2006, 2007 and 2010. DNI measurements for Murcia have been carried out by the Meteorology State Agency (Agencia Estatal de Meteorología, AEMET) from 2005 to 2010. And DNI measurements for Jaén have been carried out by the University of Jaén in 2001, 2002, 2003 and 2010. In every case, a pyrheliometer with wavelength range from 0.2 to 4 μm has been used for the DNI measurements.

SoDa website disseminates the HelioClim (HC) databases which contain radiation values at ground level obtained from the processing of the images taken by Meteosat satellites. In this case, the HC databases are processed by MINES ParisTech. On the other hand, NASA-SSE release 6 combines results from GEWEX/SRB 3 and ISCCP projects with NCAR reanalysis products (1983–2005). The database directly provides monthly and annual DNI values around the world. Finally, PVGIS includes solar radiation developed by a combination of solar radiation models and interpolated ground observations, representing the period 1981–1990. It does not directly provide DNI but this can be estimated from global and diffuse radiation components.

Table 1 compares measured values taken from the meteorological stations to values provided by the databases. Annual DNI value measured at Madrid is 1882 $kW\,h/m^2$ while the different databases give values between 1814 and 1964 $kW\,h/m^2$. This implies an error between −3.6% and 4.4%. Annual DNI value

Table 1
Annual DNI values for three Spanish locations ($kW\,h/m^2$).

Location	Measured	SoDa	NASA-SSE	PVGIS
MADRID	1882	1947	1964	1814
MURCIA	1961	1738	1905	1870
JAÉN	1984	2208	2132	1745

measured at Murcia is 1961 kW h/m^2 while the different databases give values between 1738 and 1905 kW h/m^2. This implies an error between −11.4% and −2.9%. And annual DNI value measured at Jaén is 1984 kW h/m^2 while the different databases give values between 1745 and 2208 kW h/m^2. This implies an error between −12.0% and 11.3%. Fig. 1 shows the annual DNI error for the three databases. A clear trend cannot be observed, although PVGIS underestimates DNI for these three locations and the three databases underestimate Murcia's DNI value. As a conclusion, it can be assumed that it is difficult to get reliable DNI data because each database gives different values and thus, there are sources of uncertainty.

Other authors have reported the same conclusions about uncertainty [16,17]. Šúri et al. [16] cross-compared maps of annual DNI from five databases offering solar resource and climate data for Europe: Meteonorm [18], NASA-SSE [19], PVGIS [20], Satel-Light [21] and SOLEMI [22]. From these databases, the following maps were calculated: (1) overall average estimated by a simple averaging, (2) five maps of differences to the average, and (3) standard deviation. While maps of differences show the deviation of the particular dataset from the overall average, the standard deviation indicates user's uncertainty given by the magnitude of differences between the combined data sources. Results show that 90% of the analyzed area presents an uncertainty in annual DNI, expressed by relative standard deviation, of up to 17%. This high uncertainty indicates that it is necessary to improve the databases and the radiation models. Some efforts have been made in this field. For instance, the MESoR project [17], funded by the European Commission, reduces the associated uncertainty by setting up standard benchmarking rules and measures for comparing the databases, user guidance to the application of resource data and unifying access to various databases.

Below, a very simple procedure for the calculation of DNI based on previous existing models is presented. It can be easily implemented in a spreadsheet or in computer applications in renewable energy. The aim of the proposed procedure is not to provide high accuracy. It tries to meet the basic requirements for the analysis of CPV systems by providing DNI errors similar to those of the different meteorological databases. Inputs of the procedure are the global horizontal irradiation values which, unlike DNI values, are often measured in the meteorological stations and are easy to find. The procedure does not improve the existing methods but is an easy-to-use choice useful for teaching and providing acceptable accuracy.

3. Description of the proposed method

In this section, a procedure that calculates DNI values from global horizontal irradiation values is presented.

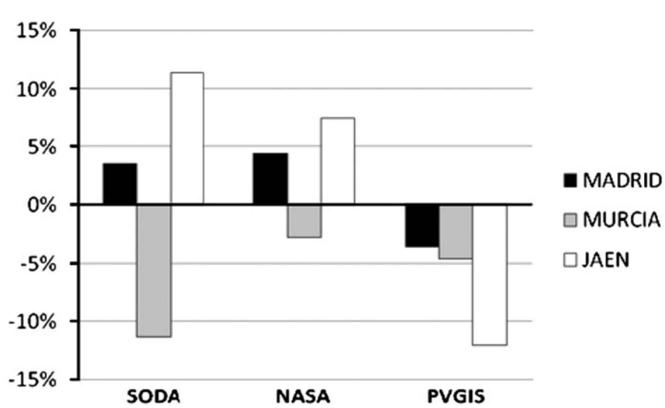


Fig. 1. Annual DNI error for the selected locations and databases.

In what follows, according to [23,24], letter G will be used to indicate irradiance or the power incident on a surface per unit area of surface (units: W/m^2) and letter H will be used to indicate irradiation or the energy incident on a surface over a specified period of time per unit area of surface (units: W h/m^2).

At the high concentration rates involved in High Concentration Photovoltaic (HCPV) systems, time resolution as well as uncertainty in radiation data play a complex role [25]. However, some authors have proven that the complexity of a solar radiation model needed for yearly energy calculations is very low [26]. Twelve values of monthly mean solar irradiation are enough to estimate yearly energy with small errors. Also, time resolutions shorter than hourly samples do not significantly improve the energy estimation results.

So, the start-up data required for the calculations are the site latitude, φ, and the twelve values of monthly average daily global irradiation on a horizontal surface, $H_{Gdm}(0)$. Results of the method are the monthly average direct normal irradiance at one hour intervals for the twelve months of the year, $G_{B\ hm}(S)$, the twelve values of monthly average daily direct normal irradiation, $H_{B\ dm}(S)$, and the value of the annual direct normal irradiation, $H_{B\ a}(S)$. The proposed method performs the sequence shown in Fig. 2 in order to calculate the DNI values.

The method is based on easy-to-use equations proposed by several authors [27] which provide a good approximation for a wide range of latitudes. Other more accurate equations and correlations [28–30] have not been taken into account because of their complexity or because they are only valid for a specific area.

The proposed method is based on the following procedure:

I. Solar declination of the day in the middle of each month, in radians, δ_{dn} [31]:

$$\delta_{dn} = \frac{23.45\pi}{180}\sin\left(2\pi \times \frac{d_n + 284}{365}\right) \quad (1)$$

where d_n is the day number of the year, ranging from 1 on January 1 to 365 on December 31. The values corresponding to January 15, February 15, March 15, etc. will be used.

II. Eccentricity correction factor of the earth's orbit of the day in the middle of each month, dimensionless, $\varepsilon_{O\ dm}$ [32]:

$$\varepsilon_{O\ dm} = 1 + 0.033 \times \cos\left(2\pi \times \frac{d_n}{365}\right) \quad (2)$$

III. Sunrise hour angle of the day in the middle of each month, in radians, $\omega_{s\ dm}$ [33]:

$$\omega_{sdm} = -\cos^{-1}(-\tan\delta_{dn} \times \tan\varphi) \quad (3)$$

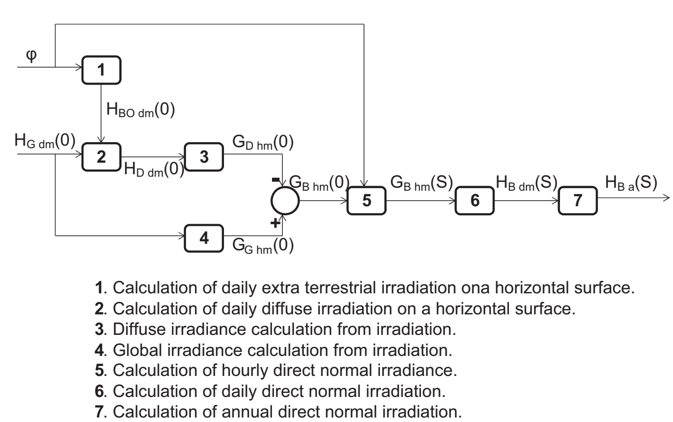


Fig. 2. Flow diagram of the proposed method.

IV. Monthly average daily extraterrestrial irradiation on a horizontal surface of each month, in W h/m^2, $H_{BO\ dm}(0)$ [34]:

$$H_{BO\ dm}(0)=\frac{24}{\pi}B_0\times\varepsilon_{O\ dm}\times(\cos\varphi\cdot\cos\delta_{dn})\times(\omega_{sdm}\times\cos\omega_{sdm}-\sin\omega_{sdm}) \quad (4)$$

being $B_0=1367$ W/m^2 the solar constant [35]. It is assumed that the extraterrestrial irradiation of the day in the middle of each month almost equals the monthly average daily extraterrestrial irradiation of this month.

V. Monthly average clearness index, dimensionless, K_{Tm} [36]:

$$K_{Tm}=H_{Gdm}(0)/H_{BOdm}(0) \quad (5)$$

VI. Monthly average diffuse fraction of global radiation, dimensionless, K_{Dm} [37]:

$$K_{Dm}=1-1.13K_{Tm} \quad (6)$$

VII. Monthly average daily diffuse irradiation on a horizontal surface of each month, in Wh/m^2, $H_{D\ dm}(0)$:

$$H_{D\ dm}(0)=H_{Gdm}(0)\times K_{Dm} \quad (7)$$

VIII. Monthly average daily direct irradiation on a horizontal surface of each month, in W h/m^2, $H_{B\ dm}(0)$:

$$H_{B\ dm}(0)=H_{G\ dm}(0)-H_{D\ dm}(0) \quad (8)$$

IX. Monthly average hourly diffuse irradiance on a horizontal surface, in W/m^2, $G_{D\ hm}(0)$ [38]:

$$G_{D\ hm}(0)=H_{D\ dm}(0)\frac{\pi}{24}\times\left(\frac{\cos\omega-\cos\omega_{s\ dm}}{\omega_{s\ dm}\times\cos\omega_{sdm}-\sin\omega_{s\ dm}}\right) \quad (9)$$

where ω is the solar hour angle in radians ($-\pi$ for 0:00 hours and $+\pi$ for 24:00 hours). Irradiance values are calculated at one hour intervals ($\Delta\omega=2\pi/24$ rad).

X. Monthly average hourly global irradiance on a horizontal surface, in W/m^2, $G_{G\ hm}(0)$ [39]:

$$G_{G\ hm}(0)=H_{G\ dm}(0)\frac{\pi}{24}(a+b\times\cos\omega)\left(\frac{\cos\omega-\cos\omega_{sdm}}{\omega_{s\ dm}\times\cos\omega_{sdm}-\sin\omega_{s\ dm}}\right) \quad (10)$$

where a and b parameters are calculated by the formulae:

$$a=0.4090-0.5016\sin(\omega_{s\ dm}+1.047) \quad (11)$$

$$b=0.6609+0.4767\sin(\omega_{s\ dm}+1.047) \quad (12)$$

XI. Monthly average hourly direct irradiance on a horizontal surface, in W/m^2, $G_{B\ hm}(0)$:

$$G_{B\ hm}(0)=G_{G\ hm}(0)-G_{D\ hm}(0) \quad (13)$$

XII. Monthly average hourly direct normal irradiance, in W/m^2, $G_{B\ hm}(S)$ [40]:

$$G_{Bhm}(S)=\frac{G_{B\ hm}(0)}{\sin\delta_{dn}\times\sin\varphi+\cos\delta_{dn}\times\cos\varphi\times\cos\omega} \quad (14)$$

XIII. Monthly average daily direct normal irradiation, in Wh/m^2, $H_{B\ dm}(S)$:

$$H_{B\ dm}(S)\approx\sum_{j=1}^{24}G_{B\ hmj}(S)\times\Delta t \quad (15)$$

where $G_{B\ hm\ j}(S)$ is the monthly average hourly direct normal irradiance at "j" hour and $\Delta t=1$ h.

XIV. Annual direct normal irradiation, in W h/m^2, $H_{B\ a}(S)$:

$$H_{B\ a}(S)\approx\sum_{i=1}^{12}dm_i\times H_{B\ dm\ i}(S) \quad (16)$$

where dm_i is the number of days for the "i" month and $H_{B\ dm\ i}(S)$ is the monthly average daily direct normal irradiation for the "i" month.

4. Results and discussion

In this section, the proposed method is applied to three Spanish locations (Madrid, Murcia and Jaén) in order to estimate both the monthly average daily direct normal irradiation of each month, $H_{B\ dm}(S)$, and the annual direct normal irradiation, $H_{B\ a}(S)$. These locations correspond to the locations analyzed in Section 2. They have been selected because ground-based measurements of annual DNI are available and thus, a comparison between measured and calculated values can be made. In what follows, irradiation values are expressed in kW h/m^2.

Table 2 shows the input data used for the calculations, i.e., the site latitude, φ, and the twelve values of monthly average daily global irradiation on a horizontal surface, $H_{G\ dm}(0)$. The global irradiation values have been obtained from PVGIS.

With these input data, the procedure described in Section 3 can be easily applied. Results are shown in Table 3, including the twelve values of monthly average daily direct normal irradiation, $H_{B\ dm}(S)$, and the value of the annual direct normal irradiation, $H_{B\ a}(S)$.

In order to compare measured and calculated DNI values, the annual DNI error has been computed for each location:

$$error(\%)=\frac{H_{B\ a}(S)_{calculated}-H_{B\ a}(S)_{measured}}{H_{B\ a}(S)_{measured}}\times 100 \quad (17)$$

Table 4 shows the results. The proposed method overestimates DNI for the three locations. Madrid's error is 3.9% while the three meteorological databases selected in Section 2 (SoDa, NASA-SSE and PVGIS) gave errors between −3.6% and 4.4%. Murcia's error is 1.2% while the databases errors were between −11.4% and −2.9%. And Jaén's error is 0.2% while the databases errors were between −12.0% and 11.3%. As a conclusion, annual DNI values produced by the proposed method are comparable to those of the existing meteorological databases. Thus, an alternative easy-to-use method can be used to compute DNI.

Table 2
Input data required by the proposed method for the three selected locations: latitude and monthly average daily global irradiation on a horizontal surface.

Location: latitude, °:	Madrid 40.417	Murcia 37.983	Jaén 37.766
Month	$H_{G\ dm}(0)$, kW h/m^2		
J	1.98	2.44	2.46
F	2.69	3.21	3.16
M	4.44	4.54	4.65
A	5.09	5.40	5.29
M	6.50	6.48	6.59
J	7.23	7.00	7.19
J	7.33	7.05	7.07
A	6.44	6.15	6.22
S	4.98	5.00	4.94
O	3.36	3.74	3.74
N	2.14	2.47	2.49
D	1.61	2.16	2.09

5. Application

The simplified procedure described in this paper can easily be used to obtain DNI data worldwide. The only requirement is to know global horizontal irradiation values for the area of interest. As these values are easy to find or measure, the proposed method becomes a very useful tool in renewable energy applications, particularly in CPV applications.

As an example of such applications, a complete map of the Spanish annual DNI is presented in Fig. 3. It has been obtained from global irradiation data of the 47 peninsular provincial capitals of Spain. For each location, annual DNI has been calculated by using a Microsoft Excel spreadsheet with the procedure described. This spreadsheet is available at http://www.ujaen.es/investiga/solar/dni.xlsx. The DNI data obtained has been graphically represented with the help of the Surfer program by Golden Software [41].

This example proves that the proposed method can be used to obtain a mass of DNI data for different regions worldwide with acceptable accuracy.

Table 3
Output data obtained by the proposed method: monthly average daily DNI of each month and annual DNI.

Location:	Madrid	Murcia	Jaén
Month	$H_{B\ dm}(S)$, kW h/m^2		
J	3.12	4.02	4.02
F	3.44	4.29	4.10
M	5.72	5.44	5.69
A	5.04	5.39	5.14
M	6.75	6.55	6.78
J	7.86	7.19	7.60
J	8.37	7.61	7.65
A	7.55	6.58	6.72
S	6.20	5.79	5.62
O	4.56	5.03	4.98
N	3.21	3.64	3.65
D	2.44	3.73	3.42
	$H_{B\ a}(S)$, kW h/m^2		
Annual	**1955**	**1985**	**1988**

Table 4
Comparison between measured annual DNI and annual DNI calculated by the proposed method.

Location	$H_{B\ a}(S)$, kW h/m^2		
	Measured	Calculated	Error (%)
Madrid	1882	1955	**3.9**
Murcia	1961	1985	**1.2**
Jaén	1984	1988	**0.2**

6. Conclusions

DNI data provided by the existing meteorological databases is obtained from satellite images and ground-based measurements by using different methods, input data and base years. While these databases are a useful tool in renewable energy applications, they present uncertainty.

A simplified procedure for estimating DNI from global irradiation based on previous existing models has been developed. It provides accuracy similar to that of the existing databases. As global irradiation data are easy to find or measure, the method becomes a good choice for the design and analysis of CPV and other renewable energy systems. It can be easily implemented in computer programs and is useful for teaching.

The accuracy of the method has been shown by comparing calculated and measured DNI for three Spanish locations. Also, the estimation error has been compared with the errors provided by three existing databases. Results indicate that the procedure can be used as an alternative to other sources of DNI data.

In order to prove the ability of the proposed method to easily obtain a mass of DNI data for different areas worldwide, a map of the Spanish annual DNI has been developed and presented.

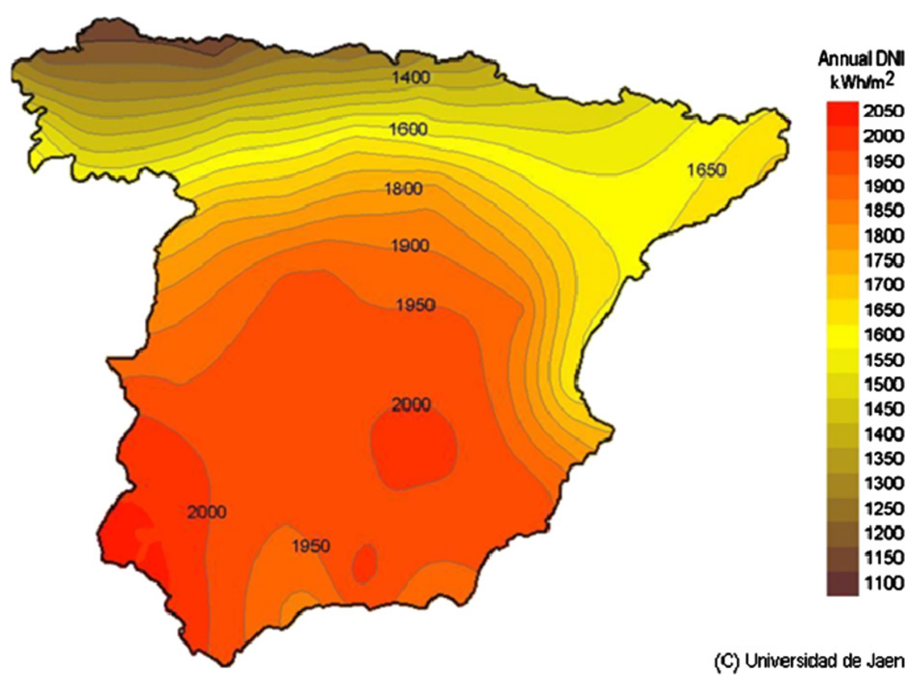


Fig. 3. Map of the Spanish annual DNI provided by the proposed method.

Acknowledgments

The authors thank José Luis Molina for his contribution as part of his final master work. This paper has been done in the framework of the project entitled "SIGMASOLES: The innovation of Concentration Photovoltaics in Spain" (PSE-440000-2009-8) funded by the Spanish Ministry of Science and Innovation.

References

[1] Luque A, Andreev V, editors. Berlin, Heidelberg: Springer-Verlag; 2007.
[2] Sala G, Pachón D, Antón I. Test, rating and specification of PV concentrator components and systems, C-rating project, Book 1: Classification of PV concentrators, Contract NNE-1999-00588.
[3] Hall IJ, Prairie RR, Anderson HE, Boes EC. Generation of typical meteorological years for 26 SOLMET stations, SAND78-1601. Alburquerque NM: Sandia National Laboratories; 1978.
[4] Ineichen P, Perez R, Kmiecik M, Renne D. Modeling direct irradiance from GOES visible channel using generalized cloud indices, Proceedings of AMS annual meeting, Long Beach, CA, 2000, pp. 133–136.
[5] Perez R, Ineichen P, Moore K, Kmiecik M, Chain C, George R, et al. A new operational model for satellite-derived irradiances: description and validation. Solar Energy 2002;73:307–17.
[6] Schillings C, Mannstein H, Meyer R. Operational method for deriving high resolution direct normal irradiance from satellite data. Solar Energy 2004;76:475–84.
[7] Martins FR, Pereira EB, Abreu SL. Satellite-derived solar resource maps for Brazil under SWERA project. Solar Energy 2007;81:517–28.
[8] Janjai S. A method for estimating direct normal solar irradiation from satellite data for a tropical environment. Solar Energy 2010;84:1685–95.
[9] Meteotest. On line 24/4/2012 in 〈http://meteonorm.com/products/meteonorm-dataset〉.
[10] Atmospheric Science Data Center, NASA. On line 24/4/2012 in 〈http://eosweb.larc.nasa.gov/sse〉.
[11] Institute for Energy and Transport, European Commission. On line 24/4/2012 in 〈http://re.jrc.ec.europa.eu/pvgis/apps4/pvest.php#〉.
[12] Energy, Environment, and Sustainable Development programme, European Commission. On line 24/4/2012 in 〈http://pvsat.de/rahmen.html〉.
[13] International Energy Agency, task 36: Solar Resource Knowledge Management. On line 24/4/2012 in 〈http://www.satel-light.com/core.htm〉.
[14] Transvalor. On line 24/4/2012 in 〈http://www.soda-is.com/eng/services/service_invoke/gui.php?xml_descript=hc3v3_invoke_hour_dni_demo.xml&Submit=HC3v3hourDNI〉.
[15] Institut für Technische Thermodynamik. On line 24/4/2012 in 〈http://www.dlr.de/tt/desktopdefault.aspx/tabid-2885/4422_read-6581〉.
[16] Šúri M, Remund J, Cebecauer T, Hoyer-Klick C, Dumortier D, Huld T, et al., Comparison of direct normal irradiation spatial products for Europe, solar paces conference, Berlin, Germany, 2009.
[17] Hoyer-Klick C, Beyer HG, Dumortier D, Schroedter-Homscheidt M, Wald L, Martinoli M, et al., MESoR—Management and exploitation of solar resource knowledge, Solar paces conference, Berlin, Germany, 2009.
[18] Remund J, Kunz S, Schilter C, Müller S. Handbook of Meteonorm version 6, part II: Theory, 2010.
[19] NASA, Surface meteorology and solar energy (SSE) release 6.0 methodology, version 3.0, 2011.
[20] Šúri M, Huld T, Dunlop ED, Cebecauer T. Geographic aspects of photovoltaics in Europe: contribution of the PVGIS website. IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing 2008;1:34–41.
[21] Dumortier D, Fontoynont M Heinemann D, Hammer A, Olseth JA, Skartveit A, et al., Satel-Light, a www server which provides high quality daylight and solar radiation data for Western and Central Europe, CIE 24th Session, Warsaw, 1999, pp. 277–281.
[22] Meyer R, Hoyer C, Schillings C, Trieb F, Diedrich E, Schroedter M. SOLEMI: a new satellite-based service for high resolution and precision solar radiation data for Europe, Africa and Asia, ISES Solar World Congress, 2003.
[23] Beckman WA, Bugler JW, Cooper PI, Duffie JA, Dunkle RV, Glaser PE, et al. Units and symbols in solar energy. Solar Energy 1978;21:65–8.
[24] Selçuk MK. Glossary of terms used in solar energy. Solar Energy 1984;33:97–114.
[25] Viana TS, Rüther R, Martins FR, Pereira EB. Assessing the potential of concentrating solar photovoltaic generation in Brazil with satellite-derived direct normal irradiation. Solar Energy 2011;85:486–95.
[26] Perpiñan O, Lorenzo E, Castro MA, Eyras R. On the complexity of radiation models for PV energy production calculation. Solar Energy 2008;82:125–31.
[27] Iqbal M. An introduction to solar radiation. Toronto: Academic Press; 1983.
[28] Liu BYH, Jordan RC. The interrelationship and characteristic distribution of direct, diffuse and total solar radiation. Solar Energy 1960;4:1–19.
[29] Iqbal M. A study of Canadian diffuse and total solar radiation data. Solar Energy 1979;22:81–90.
[30] Louche A, Notton G, Poggi P, Simonnot G. Correlations for direct normal and global horizontal irradiation on a French Mediterranean site. Solar Energy 1991;46:261–6.
[31] Cooper PI. The absorption of solar radiation in solar stills. Solar Energy 1969;12:333–46.
[32] Duffie JA, Beckman WA. Solar engineering of thermal processes. New York: Wiley; 2006.
[33] Walraven R. Calculating the position of the sun. Solar Energy 1978;20:393–7.
[34] Klein SA. Calculation of monthly average insolation on tilted surfaces. Solar Energy 1977;19:325–9.
[35] Allen CW. Solar radiation. Quarterly Journal of the Royal Meteorological Society 1954;84:307–18.
[36] Klein SA, Beckman WA, Duffie JA. TRNSYS—A transient simulation program, ASHRA. Transactions 1976;82:623–33.
[37] Page JK. The estimation of monthly mean values of daily total short-wave radiation on vertical and inclined surfaces from sunshine records for latitudes 40°N–40°S, Proceedings of U. N. Conf. New Sources of Energy, Rome, Italy, 1961, pp. 378–390.
[38] Whillier A. The determination of hourly values of total solar radiation from daily summations,. Archiv für Meteorologie Geophysik und Bioklimatologie Serie B 1956;7(2):197–204.
[39] Collares-Pereira M, Rabl A. The average distribution of solar radiation-correlations between diffuse and hemispherical and between daily and hourly insolation values. Solar Energy 1979;22:155–64.
[40] Lorenzo E, Araujo G, Cuevas A, Egido M, Miñano J, Zilles R. Solar electricity. Engineering of photovoltaic systems.Earthscan Publications Ltd.; 1994.
[41] Goldensoftware. On line 24/4/2012 in 〈http://www.goldensoftware.com/products/surfer/surfer.shtml〉.